Neutrino Physics Without Oscillations

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Abstract. There is a tremendous potential for neutrinos to yield valuable new information about strongly interacting systems. Here we provide a taste of this potential, beginning with the existence of a rigorous sum rule for the proton and neutron spin structure functions based on the measurement of the flavor singlet axial charge of the nucleon. We also comment on the NuTeV report of a 3σ deviation of the value of $\sin^2\theta_W$ measured in neutrino (and anti-neutrino) scattering from that expected within the Standard Model.

1. INTRODUCTION

Apart from rather old bubble chamber experiments we have no data for neutrino interactions with free protons. In spite of this, neutrino measurements on nuclei have given very important information on the internal structure of the nucleon. For example, this is the best source of information on the shape of the anti-quark parton distribution functions – even though, as we mention below, the understanding of nuclear corrections for neutrino beams is in a very rudimentary state. The axial form factor of the nucleon provides important guidance in dealing with low energy interactions of pions with nucleons and the nucleon-nucleon force. In comparison with the axial and electromagnetic transition form factors to baryon excited states it can also yield new insight into the dynamics of hadron structure [1].

Sum rules play a crucial role in strong interaction physics as, ideally, they are model independent – linking different experiments. The failure of such a sum rule indicates a serious change to our understanding of the strong interaction – the failure of some symmetry or of QCD itself. The famous Ellis-Jaffe sum rule, which failed in the so-called "spin crisis", was not in this category as it required a dynamical assumption (the absence of strange quarks in the nucleon). On the other hand, it is not widely appreciated that developments in the application of Witten's renormalization group methods [2] to the flavor singlet axial axial charge of the nucleon mean that we *do* now have a rigorous sum rule for the leading twist spin structure functions of the nucleon [3, 4]. This is discussed in Sect. 2, where the importance of measuring neutrino-nucleon elastic scattering is emphasised.

In Sect. 3 we discuss recent developments in the interpretation of the reported 3σ deviation from the Standard Model expectation for $\sin^2\theta_W$ in neutrino nucleus scattering. There is a recent model independent result for the correction associated with charge symmetry violation in the parton distribution functions which reduces the anomaly to no more than 2σ [5]. In addition, there are major issues concerning our understanding of

shadowing in neutrino interactions with nuclei which urgently need attention – both in connection with the NuTeV claim [6] and more generally in connection with the possible systematic errors in our knowledge of the flavor dependence of parton disributions.

2. A RIGOROUS SUM RULE FOR SPIN DEPENDENT DEEP INELASTIC SCATTERING

In polarised deep inelastic scattering at a scale, Q^2, where three flavors of quark are "active", the first moment of the nucleon spin structure function, g_1, may be written as a linear combination of the iso-triplet, SU(3) octet and flavour singlet, scale-invariant axial charges of the nucleon [7, 8, 9, 10]:

$$\int_0^1 dx\, g_1^p(x, Q^2) = \left(\frac{1}{12}g_A^{(3)} + \frac{1}{36}g_A^{(8)}\right)C_{NS}(Q^2) + \frac{1}{9}g_A^{(0)}|_{\text{inv}}C_S(Q^2) + \mathcal{O}\left(\frac{1}{Q^2}\right). \quad (1)$$

Here C_{NS} and C_S are, respectively, the flavour non-singlet and flavour singlet Wilson coefficients, which have been evaluated to three-loops in Ref. [9]:

$$C_{NS}(Q^2) = \left[1 - \frac{\alpha_s}{\pi} - 3.58\left(\frac{\alpha_s}{\pi}\right)^2 - 20.21\left(\frac{\alpha_s}{\pi}\right)^3\right]$$

$$C_S(Q^2) = \left[1 - \frac{\alpha_s}{3\pi} - 0.55\left(\frac{\alpha_s}{\pi}\right)^2 - 4.45\left(\frac{\alpha_s}{\pi}\right)^3\right]. \quad (2)$$

The isotriplet axial charge, $g_A^{(3)}$:

$$2ms_\mu\, g_A^{(3)} = \langle p, s| \left(\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d\right) |p, s\rangle, \quad (3)$$

is measured in neutron beta-decay, while the octet axial charge, $g_A^{(8)}$:

$$2ms_\mu\, g_A^{(8)} = \langle p, s| \left(\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d - 2\bar{s}\gamma_\mu\gamma_5 s\right) |p, s\rangle, \quad (4)$$

is measured in hyperon beta-decays. The Ellis-Jaffe sum rule [11] was based on the dynamical assumption that the strange quark content of the nucleon was negligible, in which case the scale-invariant, flavor singlet axial charge would be equal to the octet axial charge. The failure of that sum rule [12, 13, 14, 15] led to a completely new appreciation of the role of the axial anomaly in QCD, as well as the possibility that a substantial fraction of the spin of the proton might reside on polarized glue.

Recently, Bass, Crewther, Steffens and Thomas (BCST) [3] have shown how the 3-flavour, scale-invariant, flavour-singlet axial charge of the nucleon can be determined independently by systematically correcting elastic neutrino-proton scattering data for heavy-quark contributions. With this result we have a **rigorous sum rule** relating deep inelastic scattering in the Bjorken region of high energy and momentum transfer to three independent, low energy measurements. As with the Bjorken sum rule, the verification of this new proton spin sum rule is a crucial test of QCD itself.

The scale-invariant flavour singlet axial charge, $g_A^{(0)}|_{\text{inv}}$, is defined by [8, 9]:

$$2ms_\mu \left. g_A^{(0)} \right|_{\text{inv}} = \langle p,s | \mathscr{S}_\mu(0) | p,s \rangle \tag{5}$$

where

$$\mathscr{S}_\mu(x) = E(g) J_{\mu 5}^{GI}(x) \tag{6}$$

is the product of the gauge-invariantly renormalized singlet axial-vector operator

$$J_{\mu 5}^{GI} = \left(\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d + \bar{s}\gamma_\mu\gamma_5 s \right)_{GI} \tag{7}$$

in three flavour QCD and the renormalisation group factor

$$E(g) = \exp \int_0^g dg'\, \gamma(g')/\beta(g')\,. \tag{8}$$

Here $\beta(g)$ and $\gamma(g)$ are the Callan-Symanzik functions associated with the gluon coupling constant g and the composite operator $J_{\mu 5}^{GI}$. Finally then, the renormalization group invariant, singlet axial charge is (for three active flavors):

$$
\begin{aligned}
\left. g_A^{(0)} \right|_{\text{inv}} &= E_3(\alpha_3) \left(\Delta u + \Delta d + \Delta s \right)_3 \\
&= \left(\Delta u + \Delta d + \Delta s \right)_{\text{inv}}.
\end{aligned} \tag{9}
$$

The non-perturbative factor $E(g)$ in Eq.(6) arises naturally from the coefficient function of $J_{\mu 5}^{GI}$ in the product of electromagnetic currents $J_\alpha(x)J_\beta(0)$ at short distances, $x_\mu \sim 0$. It compensates for the scale dependence of $J_{\mu 5}^{GI}$ caused by the anomaly [16, 17, 18, 19] in its divergence

$$\partial^\mu J_{\mu 5}^{GI} = 2f\partial^\mu K_\mu + \sum_{i=1}^f 2im_i\bar{q}_i\gamma_5 q_i\,, \tag{10}$$

where K_μ is a renormalized version of the gluonic Chern-Simons current, and the number of flavours, f, is three. A consequence of the renormalization-scale invariance of $\mathscr{S}_\mu$ is that its spatial components have operator charges

$$S_i(t) = \int d^3x\, \mathscr{S}^i(t,\mathbf{x})\,, \tag{11}$$

which satisfy an equal-time algebra [8]

$$[S_i(t), S_j(t)] = i\varepsilon_{ijk}S_k(t)\,, \tag{12}$$

characteristic of spin operators, whereas the operator charges $\int d^3x J_{i5}^{GI}(t,\mathbf{x})$ do not [20].

Elastic νp scattering measures the neutral-current axial charge $g_A^{(Z)}$

$$2ms_\mu\, g_A^{(Z)} = \langle p,s | J_{\mu 5}^Z | p,s \rangle\,, \tag{13}$$

where

$$J_{\mu 5}^{Z} = \frac{1}{2}\left\{\sum_{q=u,c,t} - \sum_{q=d,s,b}\right\}\bar{q}\gamma_\mu\gamma_5 q. \tag{14}$$

As this is a six flavour quantity one must correct for the heavy flavours t, b and c which do not contribute to deep inelastic scattering for Q^2 below (say) 10 GeV^2. By applying the renormalization group techniques of Witten, and in particular by introducing appropriate "matching functions", BCST were able to sum all large logarithms appearing to NLO (the technique can be applied systematically to any order) in the heavy quark masses, with the result [3]:

$$\begin{aligned} 2g_A^{(Z)} &= \left(\Delta u - \Delta d - \Delta s\right)_{\text{inv}} + \mathscr{P}\left(\Delta u + \Delta d + \Delta s\right)_{\text{inv}} \\ &+ O(m_{t,b,c}^{-1}), \end{aligned} \tag{15}$$

where $\mathscr{P}$ is a polynomial in the running couplings

$$\begin{aligned} \mathscr{P} &= \frac{6}{23\pi}\left(\alpha_b - \alpha_t\right)\left\{1 + \frac{125663}{82800\pi}\alpha_b + \frac{6167}{3312\pi}\alpha_t - \frac{22}{75\pi}\alpha_c\right\} \\ &- \frac{6}{27\pi}\alpha_c - \frac{181}{648\pi^2}\alpha_c^2 + O\left(\alpha_{t,b,c}^3\right). \end{aligned} \tag{16}$$

Here α_t, α_b and α_c are rigorously defined simultaneous running couplings. The factor $\alpha_b - \alpha_t$ ensures that all contributions from b and t quarks cancel for $m_t = m_b$.

The final step in deriving the sum rule is then to realize that

$$\left(\Delta u - \Delta d - \Delta s\right)_{\text{inv}} = g_A^{(3)} + \frac{1}{3}g_A^{(8)} - \frac{1}{3}g_A^{(0)}\big|_{\text{inv}}. \tag{17}$$

Using Eqs.(15), (16) and (17), one can extract the value of $g_A^{(0)}\big|_{\text{inv}}$ and Eq.(1) is then a rigorous sum rule. As a result, the accurate measurement of the Z^0 axial coupling to the proton (or neutron) should be an extremely high priority.

3. THE NUTEV ANOMALY

In 1973, Paschos and Wolfenstein [21] derived an expression relating the ratio of neutral-current and charge-changing neutrino interactions on isoscalar targets to the Weinberg angle:

$$R^- \equiv \frac{\frac{1}{\rho_0^2}\left(\langle\sigma_{NC}^{\nu N_0}\rangle - \langle\sigma_{NC}^{\bar{\nu} N_0}\rangle\right)}{\langle\sigma_{CC}^{\nu N_0}\rangle - \langle\sigma_{CC}^{\bar{\nu} N_0}\rangle} = \frac{1}{2} - \sin^2\theta_W. \tag{18}$$

In Eq.(18), $\langle\sigma_{NC}^{\nu N_0}\rangle$ and $\langle\sigma_{CC}^{\nu N_0}\rangle$ are respectively the neutral-current and charged-current inclusive, total cross sections for neutrinos on an isoscalar target. The quantity $\rho_0 \equiv M_W/(M_Z\cos\theta_W)$ is one in the Standard Model. The NuTeV group recently measured neutrino charged-current and neutral-current cross sections on iron [22], finding

$\sin^2 \theta_W = 0.2277 \pm 0.0013$ (stat) ± 0.0009 (syst). This value is three standard deviations above the measured fit to other electroweak processes, $\sin^2 \theta_W = 0.2227 \pm 0.00037$ [23]. The discrepancy between the NuTeV measurement and determination of the Weinberg angle from electromagnetic measurements is surprisingly large, and may constitute evidence of physics beyond the Standard Model.

As the NuTeV experiment did not strictly measure the Paschos-Wolfenstein ratio, there are a number of additional corrections that need to be considered, such as shadowing [6], asymmetries in s and $\bar{s}$ distributions [24], asymmetries in c and $\bar{c}$ distributions [25], charge asymmetric valence parton distributions [5, 26], and so on. Reference [27] provides an excellent summary of possible corrections to the NuTeV result from within and outside the Standard Model.

3.1. Model Independence of the Charge Symmetry Correction

Londergan and Thomas recently calculated corrections to the NuTeV experiment arising from charge symmetry violation CSV) caused by the small difference of u and d quark masses [26]. This calculation followed earlier work on CSV in parton distributions [28, 29], and involved calculating CSV distributions at a low momentum scale, appropriate to a valence-dominated quark model, and using QCD evolution to generate the CSV distributions at the Q^2 values appropriate for the NuTeV experiment. The result was a correction to the NuTeV result $\Delta R_{CSV} \sim -0.0015$. This would reduce the reported effect from 3 to 2 standard deviations. Following this, NuTeV reported their own estimate of the CSV parton distributions, using a rather different procedure [30]. They obtained a much smaller correction, $\Delta R_{CSV} \sim +0.0001$. The large discrepancy between these two results suggested that the CSV correction might be strongly model dependent.

This question was recently resolved by Londergan and Thomas [5], as we now summarise. The charge symmetry violating contribution to the Paschos-Wolfenstein ratio has the form

$$\Delta R_{CSV} = \left[3\Delta_u^2 + \Delta_d^2 + \frac{4\alpha_s}{9\pi} \left(\bar{g}_L^2 - \bar{g}_R^2 \right) \right] \left[\frac{\delta U_v - \delta D_v}{2(U_v + D_v)} \right] \tag{19}$$

where

$$\begin{aligned} \delta Q_v &= \int_0^1 x \delta q_v(x) \, dx \\ \delta d_v(x) &= d_v^p(x) - u_v^n(x) \,; \qquad \delta u_v(x) = u_v^p(x) - d_v^n(x) \,. \end{aligned} \tag{20}$$

The denominator in the final term in Eq. (19) gives the total momentum carried by up and down valence quarks, while the numerator gives the charge symmetry violating momentum difference – for example, δU_v, is the total momentum carried by up quarks in the proton minus the momentum of down quarks in the neutron. This ratio is completely independent of Q^2 and can be evaluated at any convenient value.

Using an analytic approximation to the charge symmetry violating valence parton distributions that was initially proposed by Sather [28], one can evaluate Eq.(19) at a

low scale, Q_0^2, appropriate for a (valence dominated) quark or bag model [31, 32]. The advance over earlier work was to realize that for NuTeV we need only the first moments of the CSV distribution functions and these could be obtained analytically. The result for the moment of the CSV down valence distribution, δD_v, is

$$
\begin{aligned}
\delta D_v &= \int_0^1 x \left[-\frac{\delta M}{M} \frac{d}{dx}(x d_v(x)) - \frac{\delta m}{M} \frac{d}{dx} d_v(x) \right] dx \\
&= \frac{\delta M}{M} \int_0^1 x d_v(x) \, dx + \frac{\delta m}{M} \int_0^1 d_v(x) \, dx = \frac{\delta M}{M} D_v + \frac{\delta m}{M},
\end{aligned}
\tag{21}
$$

while for the up quark CSV distribution it is

$$
\begin{aligned}
\delta U_v &= \frac{\delta M}{M} \left[\int_0^1 x \left(-\frac{d}{dx}[x u_v(x)] + \frac{d}{dx} u_v(x) \right) dx \right] \\
&= \frac{\delta M}{M} \left(\int_0^1 x u_v(x) \, dx - \int_0^1 u_v(x) \, dx \right) = \frac{\delta M}{M} (U_v - 2).
\end{aligned}
\tag{22}
$$

(Here $\delta M = 1.3$ MeV is the neutron-proton mass difference, and $\delta m = m_d - m_u \sim 4$ MeV is the down-up quark mass difference.)

Equations (21) and (22) show that the CSV correction to the Paschos-Wolfenstein ratio depend only on the fraction of the nucleon momentum carried by up and down valence quarks. At no point do we have to calculate specific CSV distributions. At the bag model scale, $Q_0^2 \approx 0.5$ GeV^2, the momentum fraction carried by down valence quarks, D_v, is between $0.2 - 0.33$, and the total momentum fraction carried by valence quarks is $U_v + D_v \sim .80$. From Eqs. (21) and (22) this gives $\delta D_v \approx 0.0046$, $\delta U_v \approx -0.0020$. Consequently, evaluated at the quark model scale, the CSV correction to the Paschos-Wolfenstein ratio is

$$
\Delta R_{CSV} \approx 0.5 \left[3 \Delta_u^2 + \Delta_d^2 \right] \frac{\delta U_v - \delta D_v}{2(U_v + D_v)} \approx -0.0020.
\tag{23}
$$

Once the CSV correction has been calculated at some quark model scale, Q_0^2, the ratio appearing in Eq. (19) is independent of Q^2, because both the numerator and denominator involve the same moment of a non-singlet distribution. (Note that we have not included the small QCD radiative correction in Eq.(23).)

We stress that both Eqs. (21) and (22) are only weakly dependent on the choice of quark model scale – through the momentum fractions D_v and U_v, which are slowly varying functions of Q_0^2 and, in any case, not the dominant terms in those equations. This, together with the Q^2-independence of the Paschos-Wolfenstein ratio (Eq. (19)) under QCD evolution, explains why the previous results, obtained by Londergan and Thomas with different models and at different values of Q^2 [26], were so similar. Finally, Londergan and Thomas also demonstrated that the acceptance function calulated by NuTeV does not introduce any significant model dependence to this result.

3.2. Higher-Twist Shadowing Corrections

Although the average Q^2 of the NuTeV measurement is quoted as $16\,\mathrm{GeV}^2$, at small x the typical Q^2 is much lower and one needs to beware of possible higher-twist effects. In particular, studies of the muon nucleus scattering in a similar momentum transfer region suggest that vector meson dominance (VMD) processes can produce substantial nuclear corrections [33, 34, 35]. It is especially important that there are extensively studied differences in shadowing between photon and charged-current neutrino interactions with nuclei [36, 37]. These were important in reducing the apparently large charge synmmetry violation in an earlier NuTeV measurement [38].

As noted by Miller and Thomas [6], the same reasoning leads one to conclude that there should be a substantial difference between the VMD shadowing corrections for neutral and charged current neutrino scattering. Such a difference was not considered in the analysis of the NuTeV data. A priori, this correction is at least as large as the reported anomaly. It is difficult to estimate the systematic error associated with this as the NuTeV analysis requires that one model separately the ratios of neutral to charged current cross sections for neutrinos and anti-neutrinos and the input parton distributions are derived without higher-twist shadowing corrections from a variety of sources including electron, muon and neutrino data on protons, deuterons and nuclei. This needs a great deal more work before one can demonstrate that the problem is under control at the required level of accuracy.

4. SUMMARY

We have explained the developments in systematically correcting for heavy quark contributions to the flavor singlet axial charge of the nucleon measured in neutrino, neutral current scattering from the nucleon, which mean that we now have a rigorous spin sum rule. As a result it is now imperative to find ways to measure $g_A^{(Z)}$ accurately.

In connection with the NuTeV anomaly we now have a robust prediction for the CSV contribution to the Paschos-Wolfenstein ratio. It was possible to express the correction in terms of integrals which could be evaluated without ever specifying the shapes of the CSV distributions. Despite the fact that parton charge symmetry violation has not been directly measured experimentally, and that parton CSV effects are predicted to be quite small, we have strong theoretical arguments regarding both the sign and magnitude of these corrections. The CSV effects should make a significant contribution to the value for the Weinberg angle extracted from the NuTeV neutrino measurements, reducing the anomaly by at least one standard deviation. Finally, again in connection with the NuTeV anomaly, we noted the importance of understanding higher-twist shadowing corrections associated with VMD and particularly the corresponding systematic errors in our knowledge of parton distribution functions.

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